# SEISMIC ISOLATION BEARING


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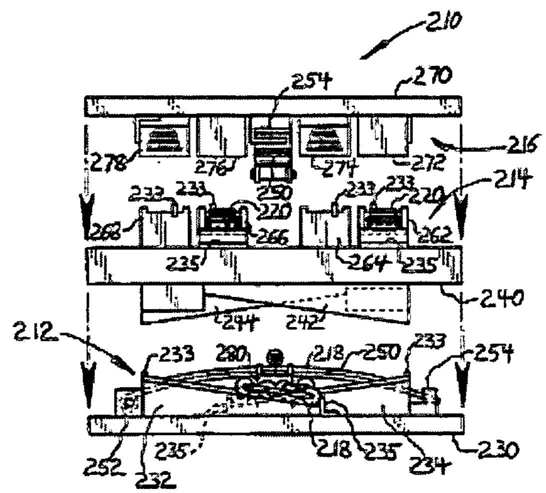
Abstract of **WO0142593**

A seismic isolation bearing includes a lower assembly, an intermediate assembly, and an upper assembly. The intermediate assembly is mounted on the lower assembly for X-axis linear movement relative to the lower assembly, and sloped wedges acting between the lower and intermediate assemblies generate a gravitational restoring force biasing the intermediate assembly back toward a neutral X-axis position with respect to the lower assembly in the event of seismically induced displacement. The upper assembly is mounted on the intermediate assembly in a similar manner for orthogonal Y-axis linear movement. Cylindrical rollers, friction reducing shoes, or low-friction interfaces are used between wedge surface portions to allow a small wedge slope angle. A buffer spring and damper unit are preferably provided between the lower and intermediate assemblies and between the intermediate and upper assemblies. Sweeper plates connected to the rollers are disclosed to provide self-cleaning of the wedge surface portions. Sacrificial and/or resiliently-mounted protective caps and sealing strips house the bearing and help shield it from environmental debris.

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(74) **Agents: SNYDER, George, L., Jr.** et al.; Simpson, Simpson & Snyder, L.L.P., 5555 Main Street, Williamsville, NY 14221 (US).

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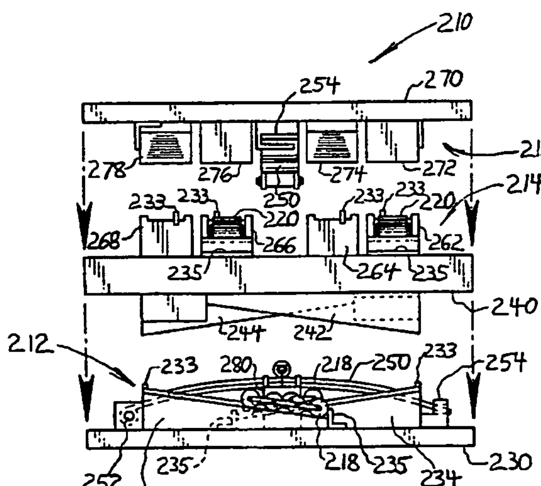
(54) **Title:** SEISMIC ISOLATION BEARING

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**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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| Y | | 17, 19-22,24 |
| X | US 1 761 660 A (F. CUMMINGS) 3 June 1930 (1930-06-03) the whole document | 1-8, 10-12, 14-16,18 |
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[X] Further documents are listed in the continuation of box C.

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| Category ° | Citation of document, with indication,where appropriate, of the relevant passages | Relevant to claim No. |
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Information on patent family members

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PCT/US 00/42377

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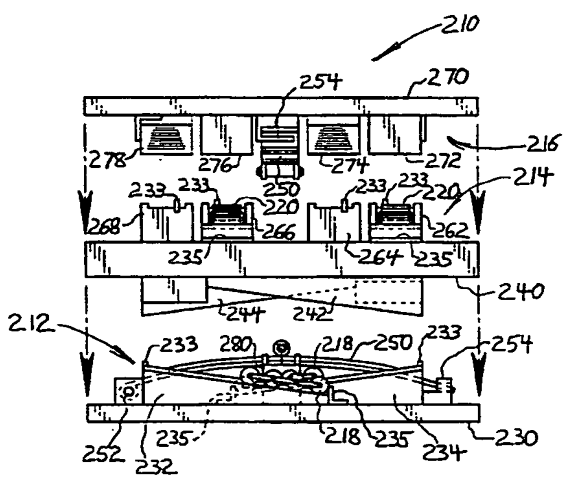


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# SEISMIC ISOLATION BEARING

## TECHNICAL FIELD

The present invention relates to devices for isolating structural members from seismic forces to minimize damage and reduce casualties in the event of an earthquake. More particularly, the present invention relates to a self-aligning seismic isolation bearing that accommodates relatively large horizontal displacements in a space efficient manner.

## BACKGROUND ART

A known design approach for improving structural response to earthquakes is based on the principle of seismic isolation, wherein energy is generally dissipated by mechanical dissipating devices such as lead cores within lead-rubber bearings, by friction in sliding bearings, or by special supplemental mechanical energy-dissipating devices such as steel, viscous or viscoelastic dampers. In order to prevent damage to main structural components, large horizontal displacements must be accommodated in the isolation bearing system.

Elastomeric isolation bearings according to the prior art typically comprise upper and lower metal plates separated by a layer of elastomeric material that allows relative horizontally directed movement between the plates and generates a restorative force. A recognized drawback of these bearings is that they must be very tall to allow for seismically induced lateral displacements of one to two feet.

Conventional sliding isolation bearing systems include an upper portion and a lower portion intended for sliding displacement with respect to the upper portion incident to horizontally directed ground excitations transmitted to the lower portion of the bearing. In a typical design, for example as described in U.S. Patent No. 5,867,951, the upper portion of the bearing includes a downwardly facing concave surface, such as a spherical surface, that is engaged by a bearing element having a contact surface of low-friction material. Sliding isolation bearings of this type are space-inefficient because the concave surface of the upper portion must be large enough to accommodate horizontal movement in all directions, thus making the upper portion unduly large. This can be a significant disadvantage where space restrictions apply, such as with a highway overpass bridge

where the bridge pier is of limited width dictated by the traversed lanes of highway. It has also been recognized that the resonant frequency of the oscillatory sliding bearing could be matched by the earthquake, leading to dangerous displacements. Another disadvantage is apparent after an earthquake has occurred: displacement is permanent, and hydraulic jacks are required to return the displaced structure to its original position, if this is possible.

Other isolation bearings allow for linear motions along orthogonal X and Y axes to achieve a resultant horizontal displacement.

U.S. Patent No. 4,596,373 to Omi et al. describes an isolation bearing comprising a base, a pair of parallel X-axis rails fixed to the base, X-axis linear motion means slidably mounted on each X-axis rail, a pair of parallel Y-axis rails fixed to the X-axis linear motion means, Y-axis linear motion means slidably mounted on each Y-axis rail, and a top platform 8 mounted on the Y-axis linear motion means. Thus, horizontal displacement between the base and the platform results from a combination of X and Y motions to isolate structure supported on the platform from ground motions transmitted to the base. Friction dampers and tension springs are associated with the X and Y linear motion means to establish a linear oscillation system.

U.S. Patent No. 5,035,394 to Haak discloses an isolation bearing comprising lower, intermediate and upper levels. An interconnection between the upper and intermediate levels includes tracks and bearings riding on the tracks to permit relative motion along a first axis, while a similar interconnection between the intermediate and lower levels permits relative motion along a second axis perpendicular to the first axis. The isolation bearing further comprises spring-biased centering and restoring mechanisms between the upper and intermediate levels and between the intermediate and lower levels.

U.S. Patent No. 5,716,037, also to Haak, teaches another three-level isolation bearing. The upper level includes two parallel guide bars fixed to an undersurface thereof for receipt by parallel rows of roller bearings on a top surface of the intermediate level to enable relative linear motion along a first axis. The intermediate level further includes opposing V-shaped cam tracks between the rows of roller bearings for receiving a spring-loaded roller-follower carried by the upper lever, whereby the upper level is urged to a

neutral axial position relative to the intermediate level, and a similar restoring arrangement is provided with respect to the lower and intermediate levels.

## DISCLOSURE OF INVENTION

Therefore, it is an object of the present invention to provide an improved seismic isolation bearing that saves space over prior art isolation bearings.

It is another object of the present invention to provide an improved seismic isolation bearing that automatically returns to an original neutral position after ground excitation ceases.

It is another object of the present invention to provide an improved seismic isolation bearing that has virtually no resonant frequencies that can be matched by an earthquake.

It is another object of the present invention to provide an improved seismic isolation bearing that has a built-in failsafe should displacement exceed expected limits.

In furtherance of these and other objects, a seismic isolation bearing of the present invention generally comprises a lower assembly, an intermediate assembly, and an upper assembly. The intermediate assembly is mounted on the lower assembly for travel in opposite X-axis directions relative to an X-axis neutral position by X-axis sloped wedges acting between the lower and intermediate assemblies to bias the intermediate assembly toward its X-axis neutral position under gravitational loading when the intermediate assembly travels away from the X-axis neutral position. Likewise, the upper assembly is mounted on the intermediate assembly for travel in opposite Y-axis directions relative to a Y-axis neutral position by Y-axis sloped wedges acting between the intermediate and upper assemblies to bias the upper assembly toward its Y-axis neutral position by gravitational loading when said upper assembly travels away from said Y-axis neutral position.

In one embodiment, the lower assembly includes two X-axis wedge surface portions on its topside that slope downward toward a central junction, the intermediate assembly includes two X-axis wedge surface portions on its underside that slope upward toward a central junction to oppose the X-axis wedge surface portions on the lower assembly, and a cylindrical roller acts between one opposing pair of X-axis wedge surface

portions in one X-axis direction and between the other opposing pair X-axis wedge surface portions in the other X-axis direction. A similar but orthogonal configuration is provided between the intermediate and upper assemblies for Y-axis travel. Accordingly, seismically induced X-axis movement of the intermediate assembly away from an X-axis neutral position and Y-axis movement of the upper assembly away from a Y-axis neutral position are each accompanied by the creation of a gravitational restorative force.

In another embodiment, a plurality of X-axis wedges are provided on the topside of the lower assembly and the underside of the intermediate assembly. Each X-axis wedge on the lower assembly has a corresponding X-axis wedge on the intermediate assembly. The pairs of corresponding X-axis wedges provide opposing parallel sloped X-axis wedge surface portions, and a roller train acts between each pair of the opposing X-axis wedge surface portions. An orthogonal arrangement of Y-axis wedges and roller trains is provided on the topside of the intermediate assembly and the underside of the upper assembly. Two spring damper assemblies are preferably provided, one between the lower and intermediate assemblies and another between the intermediate and upper assemblies.

In an alternative embodiment, the roller trains are replaced by low-friction sliding shoes designed for sliding surface-to-surface contact between opposed cooperating wedges.

In yet a further embodiment, the wedge surface portions of opposed cooperating wedges are designed to provide a low-friction surface-to-surface interface, such that the rollers or sliding shoes can be omitted.

## BRIEF DESCRIPTION OF DRAWINGS

The nature and mode of operation of the present invention will now be more fully described in the following detailed description of the preferred embodiments taken with the accompanying drawing figures, in which:

Fig. 1 is an elevational view showing a seismic isolation bearing formed in accordance with the present invention installed to support a section of a highway overpass;

Figs. 2-5 are isometric views for schematically teaching the principle of the present invention;

Fig. 6 is a partially-sectioned side elevational view of an isolation bearing formed in accordance with one embodiment of the present invention;

Fig. 7 is an exploded front elevational view of an isolation bearing formed in accordance with another embodiment of the present invention;

Fig. 8 is an exploded side elevational view of the isolation bearing shown in Fig. 7;

Fig. 9 is a top plan view of a lower assembly of the isolation bearing shown in Fig. 7;

Fig. 10 is a bottom plan view of an intermediate assembly of the isolation bearing shown in Fig. 7;

Fig. 11 is a top plan view of the intermediate assembly of the isolation bearing shown in Fig. 7;

Fig. 12 is a bottom plan view of an upper assembly of the isolation bearing shown in Fig. 7;

Figs. 13A-13E are a series of graphs illustrating kinetic characteristics of an isolation bearing formed in accordance with the present invention assuming various conditions;

Figs. 14A and 14B are graphs showing theoretical displacement and acceleration responses, respectively, of an isolation bearing according to the present invention subjected to an input excitation based on data from the Northridge earthquake;

Figs. 15A and 15B are graphs showing theoretical displacement and acceleration responses, respectively, of an isolation bearing according to the present invention subjected to an input excitation based on data from the Kobe earthquake;

Figs 16A and 16B are graphs showing theoretical displacement and acceleration responses, respectively, of an isolation bearing according to the present invention subjected to an input excitation based on data from the El Centro earthquake;

Figs 17A and 17B are graphs showing theoretical displacement and acceleration responses, respectively, of an isolation bearing according to the present invention subjected to an input excitation based on data from the Taft earthquake;

Figs. 18A and 18B are graphs showing theoretical displacement and acceleration responses, respectively, of a damped isolation bearing according to the present invention subjected to an input excitation based on data from the Northridge earthquake, assuming a first damping ratio;

Figs. 19A and 19B are graphs similar to those of Figs. 18A and 18B, respectively, however assuming a second damping ratio;

Figs 20A and 20B are graphs similar to those of Figs. 18A and 18B, respectively, however assuming a third damping ratio;

Figs 21A and 21B are graphs similar to those of Figs. 18A and 18B, respectively, however assuming a fourth damping ratio;

Figs. 22A and 22B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the El Centro earthquake;

Figs. 23A and 23B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the Taft earthquake;

Figs. 24A and 24B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the Pacoima Dam earthquake;

Figs. 25A and 25B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the Northridge earthquake;

Figs. 26A and 26B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the Kobe earthquake;

Figs. 27A and 27B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the Mexico City earthquake;

Figs. 28A and 28B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the Chi Chi (Taiwan) earthquake;

Figs. 29A and 29B are graphs showing measured displacement and acceleration responses, respectively, of an experimental isolation bearing according to the present invention subjected to a shake table input excitation based on data from the Marmara (Turkey) earthquake;

Fig. 30 is an exploded front elevational view of an isolation bearing formed in accordance with another embodiment of the present invention similar to the embodiment shown in Figs. 7-12, however using sliding shoes in place of cylindrical rollers;

Fig. 31 is a cross-sectional view of a first type of sliding shoe designed for use in the isolation bearing of Fig. 30;

Fig. 32 is a cross-sectional view of a second type of sliding shoe designed for use in the isolation bearing of Fig. 30; and

Fig. 33 is a front elevational view of an isolation bearing formed in accordance with a further embodiment of the present invention wherein a direct sliding interface is provided between cooperating wedges.

## BEST MODES FOR CARRYING OUT THE INVENTION

Referring initially to Fig. 1, an example environment for use of the present invention is a highway overpass bridge 2 having a pier 4 for supporting adjacent ends 6A and 6B of bridge substructure segments 6. Each end 6A, 6B is supported on pier 4 by an isolation bearing 10 formed in accordance with the present invention. More specifically, bearing 10 generally comprises a lower assembly 12 fixedly anchored to pier 4, an intermediate assembly 14 mounted on lower assembly 12, and an upper assembly 16 mounted on intermediate assembly 14 and attached to the respective segment end 6A, 6B.

Isolation bearings 10 are designed to accommodate any directional displacement between the bridge pier 4 and the segment ends 6A, 6B and dissipate kinetic energy in the event that seismic ground motion is transmitted through bridge pier 4, thereby minimizing damage to the roadway and increasing the safety of motorists. Of course, isolation bearings 10 can be used in many other environments. By way of further example, bearing 10 can be installed with lower assembly 12 fixed to a ground level foundation and upper assembly 16 fixed to a structural member, thereby isolating the structural member from seismic ground motion. Bearing 10 can also be installed to protect a work of art, such as sculpture, from earthquake damage.

Turning now to Figs. 2-5, the principle of operation of bearing 10 is illustrated schematically with respect to different variations on a theme. Fig. 2 shows intermediate assembly 14 mounted on lower assembly 12 by a first cylindrical roller 18 having a horizontal axis of rotation perpendicular to the X-axis of the system, thereby permitting linear motion of intermediate assembly 14 relative to lower assembly 12 directed along the X-axis. The top side of lower assembly 12 includes a pair of X-axis wedge surface portions 12A and 12B sloping downwardly in opposite X-axis directions toward one another. Meanwhile, the underside of intermediate assembly 14 includes another pair of X-axis wedge surface portions 14A and 14B sloping upwardly in opposite X-axis directions toward one another. As shown in Fig. 2, intermediate assembly 14 is at a neutral X-axis position relative to lower assembly 12, wherein roller 18 is at lowest trough 12C formed by the junction of X-axis wedge surface portions 12A and 12B, and intermediate assembly 14 is centered on roller 18 such that the crest 14C formed by the junction of the other X-axis wedge surface portions 14A and 14B is in vertical alignment with the axis of rotation of roller 18. As can be understood, when intermediate assembly 14 rolls in the positive X direction established in Fig. 2, roller 18 contacts X-axis wedge surface portions 12A and 14A. Conversely, when intermediate assembly 14 rolls in the negative X direction established in Fig. 2, roller 18 contacts X-axis wedge surface portions 12B and 14B. In either case, movement of intermediate assembly 14 away from the neutral X-axis position is accompanied by the development of a gravity-induced restoring force tending to cause roller 18 to roll back toward its equilibrium position so as to restore the intermediate assembly 14 to the neutral X-axis position shown in Fig. 2.

A similar arrangement is used to permit Y-axis motion of upper assembly 16 relative to intermediate assembly 14. Specifically, upper assembly 16 is mounted on lower assembly 12 by a second cylindrical roller 20 having a horizontal axis of rotation perpendicular to the Y-axis of the system, thereby permitting linear motion of upper assembly 16 relative to intermediate assembly 14 directed along the Y-axis. The top side of intermediate assembly 14 includes a pair of Y-axis wedge surface portions 14D and 14E sloping downwardly in opposite Y-axis directions toward one another, and the underside of upper assembly 16 includes another pair of Y-axis wedge surface portions 16D and 16E sloping upwardly in opposite Y-axis directions toward one another. As shown in Fig. 2, upper assembly 16 is at a neutral Y-axis position relative to intermediate assembly 14, wherein roller 20 is at lowest trough 14F formed by the junction of Y-axis wedge surface portions 14D and 14E and upper assembly 16 is centered on roller 20 such that the crest 16F formed by the junction of the other Y-axis wedge surface portions 16D and 16E is in vertical alignment with the axis of rotation of roller 20. Accordingly, when upper assembly 16 rolls in the positive Y direction indicated in Fig. 2, roller 20 contacts Y-axis wedge surface portions 14D and 16D. Conversely, when intermediate assembly 14 rolls in the negative Y direction, roller 20 contacts Y-axis wedge surface portions 14E and 16E. In the same manner discussed above with regard to X-axis movement, Y-axis movement of upper assembly 16 away from the neutral Y-axis position is accompanied by the development of a gravitational restoring force which biases roller 20 and upper assembly 16 toward equilibrium. At the neighborhood of the crest, there is an arcuate surface that smoothly connects surfaces, for example, surface 16D and 16E. This arcuate surface is used to reduce the impact when the roller assembly moves from one surface to another.

Figs. 3-5 show, in schematic representation, certain variations of the isolation bearing shown in Fig. 2. In Fig. 3, there are no wedge surface portions associated with intermediate assembly 14, whose top side and underside are shown as flat horizontal surfaces. Nevertheless, desired gravitational restoring forces are present with respect to the X and Y components of movement due to X-axis wedge surface portions 12A, 12B and Y-axis wedge surface portions 16D and 16E. In the variation shown in Fig. 4, neither lower assembly 12 nor upper assembly 16 includes any wedge surface portions, however

intermediate assembly 14 includes X-axis wedge surface portions 14A, 14B on its underside and Y-axis wedge surface portions 14D, 14E on its topside. Another variation is shown in Fig. 5, wherein wedge surface portions are only associated with the undersides of intermediate assembly 14 and upper assembly 16. An analogous variation, not shown, would have wedge surface portions only associated with the topsides of lower assembly 12 and intermediate assembly 14.

Progressing from the schematic representations of Figs. 2-5 to the embodiment shown in Fig. 6, an isolation bearing 110 comprises a lower assembly 112, an intermediate assembly 114, and an upper assembly 116. In Fig. 6, the X-axis runs normal to the page, while the Y-axis extends right to left across the page. Isolation bearing 110 is fundamentally formed according to the principles of bearing 10 shown in Fig. 2, with load bearing elements preferably being made of steel. Lower assembly includes an X-axis wedge surface portion 112A analogous to X-axis wedge surface portion 12A in Fig. 2, and an opposing X-axis wedge surface portion not shown due to sectioning but analogous to X-axis wedge surface portion 12B in Fig. 2. Likewise, an X-axis wedge surface portion 114B, a Y-axis wedge surface portion 114E, and a Y-axis wedge surface portion 116D of intermediate assembly 114 are also visible. Intermediate assembly 114 is mounted for travel along the X-axis relative to lower assembly 112 by a cylindrical roller 118. Gusseted walls 113 are fastened to lower assembly 112 at opposite ends of roller 118, and roller 118 includes an axel-mounted guidewheel assembly 122 at each end thereof having a guidewheel 124 for engaging walls 113 to maintain axial orientation of roller 118 as it moves back and forth along the X-axis.

Upper assembly 116 is mounted for travel along the Y-axis relative to intermediate assembly 114 by another cylindrical roller 120. Gusseted walls 115 are fastened to upper assembly 116 at opposite ends of roller 120, and roller 120 includes axel-mounted guidewheel assemblies 122 at its opposite ends for maintaining axial orientation of roller 120 as it moves back and forth along the Y-axis. Stop blocks 126 are provided to limit roller travel in the rolling fashion. Therefore, the roller or rollers will stop rolling but may continue to travel in the sliding fashion, if the ground motion is too large to allow the bearing to stop moving. For example, Y-axis wedge surface portion 116D is longer than the main plate of intermediate assembly 114 shown in Figure 6.

Because the sliding friction coefficient will be significantly larger than that of rolling friction after the roller or rollers meet the stop block, the lateral force required for movement will become significantly larger, which will provide a fail-safe mechanism to protect the bearing from excessively large displacements. A sweeper plate 128 can be connected between guidewheel assemblies 122 to push away dirt and debris from the wedge surface portions of the bearing. Similar to the upper assembly, the lower assembly also possesses the stop blocks and sweeper plate as marked by 126 and 128 in the upper portions. The functions of lower stop blocks and sweep plate are exact the same as the upper ones, except they are installed in the perpendicular directions.

In both the upper and the lower assemblies, there are a pair of protective caps 130 and 130' and a pair of sealing strips 132 and 132' in each side. They are used to prevent a certain amount of dirt and debris from entering the interior of isolation bearing 110, respectively. In the upper assembly, the cap and sealing strip will be torn off during strong earthquakes and should be replaced after the quake. However, in the lower assembly, the protective cap and sealing strip are installed with a spring-hinge such that during large displacements, the cap and sealing strip can be opened and closed repeatedly, whereas they remain closed in normal circumstances.

Both the upper and the lower assembly possess water drain holes (117 in upper assembly and 117' in lower assembly) that allow water from rain, snow or other sources to be drained away from the wedge surface portions.

Figs. 7-12 show an isolation bearing 210 formed in accordance with another embodiment of the present invention, with sidewall plates removed to expose the internal configuration of the bearing. Bearing 210 generally comprises a lower assembly 212, an intermediate assembly 214 mounted on lower assembly for X-axis linear movement relative to the lower assembly, and an upper assembly 216 mounted on the intermediate assembly for Y-axis linear movement relative to the intermediate assembly. The load bearing elements of isolation bearing 210 are preferably formed of steel.

Lower assembly 212 includes a base plate 230 having a plurality of mounting holes 231 for receiving anchoring fasteners (not shown), a plurality of parallel X-axis wedges 232, 234, 236, and 238 fixed to a top side of base plate 230, and preferably a buffer spring 250 fixed to the top side of base plate 230 and positioned centrally with

respect to the X-axis wedges 232, 234, 236, and 238. More specifically, X-axis wedges 232 and 234 are arranged as a complementary pair of wedges on one side of buffer spring 250, while X-axis wedges 236 and 238 are arranged as a complementary pair of wedges on another side of the spring damper assembly. The X-axis wedges associated with lower assembly 212 include respective X-axis wedge surface portions 232A, 234A, 236A and 238A. X-axis wedge surface portions 232A and 234A extend downwardly at a constant slope in opposite but approaching X-axis directions to define a shallow V-shaped profile as viewed in Fig. 7. As used herein, the term "approaching" indicates converging direction with respect to a single directional axis only, and does not require that the surface portions actually meet, since they may be spaced apart along another axis different from the axis of approach. For example, X-axis wedge surface portions 232A and 234A approach each other along opposite X-axis directions, but are spaced apart from each other along the Y-axis of the system so as not to physically meet. X-axis wedge surface portions 236A and 238A are arranged in a similar manner to X-axis wedge surface portions 232A and 234A, however they are on an opposite side of buffer spring 250. X-axis wedges 232, 234, 236, and 238 each include a pair of detents 233 and 235 at opposite ends of the respective X-axis wedge surface portion associated with the particular X-axis wedge. X-axis wedge surface portions 232A, 234A, 236A, and 238A are preferably bounded by elevated side curbs 237 to form a recessed track, and a roller train 218 having a plurality of cylindrical rollers is positioned on each the X-axis wedge surface portions between side curbs 237.

Intermediate assembly 214 includes a mid-plate 240 and another plurality of X-axis wedges 242, 244, 246, and 248 depending from an underside of mid-plate 240 and arranged opposite X-axis wedges 232, 234, 236, and 238, respectively. The X-axis wedges associated with intermediate assembly 214 include respective X-axis wedge surface portions 242A, 244A, 246A and 248A. X-axis wedge surface portions 242A and 244A extend upwardly at a constant slope in opposite but approaching X-axis directions to define an inverted shallow V-shaped profile as viewed in Fig. 7. X-axis wedge surface portion 242A is opposite and parallel to X-axis wedge surface portion 232A and X-axis wedge surface portion 246A is opposite and parallel to X-axis wedge surface portion 236A. Accordingly, a roller train 218 cooperating between X-axis wedge surface

portions 232A and 242A, and another roller train 218 cooperating between X-axis wedge surface portions 236A and 246A, serve to support the intermediate assembly 214 and load thereon when the intermediate assembly shifts to the left from the X-axis neutral position shown in Fig. 7. Conversely, roller trains 218 cooperating between X-axis wedge surface portions 234A and 244A and between X-axis wedge surface portions 238A and 248A carry the load when intermediate assembly 214 shifts to the right from the X-axis neutral position.

Since the coefficient of rolling friction is very small, the slope angle of the X-axis wedge surface portions can be small. In a prototype bearing built for testing, an angle of 4.5 degrees from horizontal was chosen. A self-restoring condition under gravitational loading is generally achieved where the slope angle is greater than 1 degree, however this depends upon the actual coefficient of rolling friction. Since the natural frequency of the system depends to a large extent on the slope angle, selection of the slope angle is an important design consideration. Only if the natural period of the isolation bearing exceeds the time of the major periods of seismic ground motion by a factor of 1.4 will the isolation bearing start to reduce the ground acceleration in its response. Therefore, it is desirable to have a low slope angle for a longer natural period. However, this requires that friction in the wedge action of the isolation bearing be minimized, for example by the use of roller trains 218, 220.

Buffer spring 250 is preferably in the form of a leaf spring elongated in an X-axis direction and arcuately spanning lower assembly 212. One end of buffer spring 250 is pivotally mounted at pin 252, and the opposite end of buffer spring 250 is slidably confined under a retainer bar 254. As will be appreciated, impact forces between opposing X-axis wedge surface portions and the roller trains 218 are attenuated by buffer spring 250. To gain a better understanding of the effects of buffer spring 250 on the X-axis oscillatory motion between intermediate assembly 214 and lower assembly 212, attention is now directed to Figs. 13A-13E, which plot displacement (x), velocity (v), and acceleration (a) of the intermediate assembly 214 relative to the lower assembly 212 as a function of time given an initial displacement of twelve inches and an initial velocity of zero under various friction and spring conditions, where $\mu$ is the coefficient of rolling friction, $\mu_y$ is the coefficient of lateral sliding friction, k is the spring stiffness, m is the

supported mass, and $\delta_0$ is the maximum spring deflection. It will be noted that the velocity of intermediate assembly 214 experiences "cusp" points at which the velocity vector reverses direction, and the acceleration of intermediate assembly 214 undergoes sudden change. Figs. 13B, 13C, and 13E illustrate the benefit of the buffer spring, namely that it in reduces the severity of the transitions in the velocity and acceleration curves.

It is also preferred to operably couple the mid-region of buffer spring 250 to an elastomeric damper 280 centrally located on base plate 230. In this way, vertical Z-axis separating motion between lower assembly 212 and intermediate assembly 214 resulting from wedge action is exploited to dissipate energy. The effect of damper 280 will be discussed below, following a generalized discussion of dynamic response. Alternative energy dissipating devices include fluid, friction, and metallic dampers.

Paired Figs. 14A, 14B through 17A,17B were developed based on differential equations of motion for external loading using the SIMULINK program of MATLAB to illustrate dynamic response characteristics of an isolation bearing of the present invention when the bearing subjected to different dynamic excitation inputs based on actual recorded earthquake data. For the numerical simulations, it was assumed that the angle of all wedge surface portions is 4.5 degrees, the coefficient of rolling friction is .005, the coefficient of lateral slide friction is 0.1, the supported mass is 0.08 kipssec$^2$/inch, the initial buffer spring deflection is 0.7 inches, the total spring stiffness is 13.2 kips/inch, and the damping coefficient is 0.012 kipssec/inch. Figs. 14A and 14B respectively show displacement and acceleration responses under excitation based on data recorded from the Northridge earthquake, Figs. 15A and 15B show the same responses for an input based on the Kobe earthquake, Figs. 16A and 16B show the same responses for an input based on the El Centro earthquake, and Figs. 17A and 17B show the same responses for an input based on the Taft earthquake. It can be observed that the amplitude of absolute acceleration is approximately a small constant, about 0.1g, and the amplitude of relative displacement is slightly larger than the amplitude of the earthquake wave displacement. Also, frequency resonance did not happen for any of the earthquake waves.

As mentioned above, the mid-region of buffer spring 250 is preferably connected to an elastomeric damper 280 centrally located on base plate 230. Paired Figs. 18A, 18B

through 21A, 21B illustrate the effect of viscous damping on the system's dynamic response to an earthquake wave input, in this case a wave input based on data recorded from the Northridge earthquake. Each pair of figures includes a plot of displacement versus time and a plot of acceleration versus time for a predetermined damping ratio. In Figs. 18A and 18B the damping ratio is 0 kipssec/inch, in Figs. 19A and 19B the damping ratio is 0.012 kipssec/inch, in Figs. 20A and 20B the damping ratio is 0.12 kipssec/inch, and in Figs 21A and 21B the damping ratio is 0.24 kipssec/inch. A comparison of Figs. 18A, 18B through 21A, 21B indicates that an increase in damping ratio results in a decrease in relative displacement response but an increase in absolute acceleration response. Thus, by selecting the proper damping ratio, the desired responses can be achieved.

Referring again to bearing 210, a structural system similar to the X-axis system described above is provided between intermediate assembly 214 and upper assembly 216, except that the direction of motion is perpendicular to the direction of motion between the intermediate and lower assemblies. A plurality of parallel Y-axis wedges 262, 264, 266, and 268 are fixed to a topside of mid-plate 240. The Y-axis wedges associated with intermediate assembly 214 include respective Y-axis wedge surface portions 262A, 264A, 266A and 268A. Y-axis wedge surface portions 262A and 264A extend downwardly at a constant slope in opposite but approaching Y-axis directions to define a shallow V-shaped profile as viewed in Fig. 8. Y-axis wedges 262, 264, 266, and 268 each include a pair of detents 233 and 235 at opposite ends of the respective Y-axis wedge surface portion of the Y-axis wedge, and the Y-axis wedge surface portions 262A, 264A, 266A, and 268A are preferably bounded by elevated side curbs 237. A roller train 220 having a plurality of cylindrical rollers is positioned on each the Y-axis wedge surface portions between side curbs 237.

Upper assembly 216 includes a top-plate 270 having mounting holes 271 for receiving anchoring fasteners (not shown), and another plurality of Y-axis wedges 272, 274, 276, and 278 depending from an underside of top-plate 270 and arranged opposite Y-axis wedges 262, 264, 266, and 268, respectively. Y-axis wedge surface portions 272A and 274A extend upwardly at a constant slope in opposite but approaching Y-axis directions to define an inverted shallow V-shaped profile as viewed in Fig. 8. Y-axis

wedge surface portion 272A is opposite and parallel to Y-axis wedge surface portion 262A, and Y-axis wedge surface portion 276A is opposite and parallel to Y-axis wedge surface portion 266A. Roller trains 220 cooperating between Y-axis wedge surface portions 262A and 272A and between Y-axis wedge surface portions 266A and 276A support upper assembly 216 and load thereon when the upper assembly shifts to the right from the Y-axis neutral position shown in Fig. 8. Conversely, roller trains 220 cooperating between X-axis wedge surface portions 264A and 274A and between Y-axis wedge surface portions 268A and 278A carry the load when upper assembly 214 shifts to the left from the Y-axis neutral position.

A second buffer spring 250 is preferably installed to act between the intermediate and upper assemblies. In the present embodiment, the second buffer spring is mounted on the underside of top plate 270 in an inverted manner relative to the spring damper assembly associated with base plate 230. The second buffer spring 250 on the underside of top plate 270 is rotated ninety degrees with respect to that on base plate 230, but is similar in all other respects. In addition, a second elastomeric damper 280 is preferably installed at the mid-region of second buffer spring 250 to dissipate energy.

Figs. 22A, 22B through 29A, 29B show the measurement results of a series of shake table experiments recently conducted at the State University of New York at Buffalo. The experimental isolation bearing was constructed in accordance bearing embodiment 210 of Figs. 7-12 to support a concrete block weighing 14 tons. The slope angle of all X-axis and Y-axis wedge surface portions was 4.5 degrees, inclined to center from both ends symmetrically. As the bearing moves, half of the rollers will be offset from center position, thus there are only two columns and four rows of rollers to carry the gravity load.

The limiting values of design load effect per unit length $P_{pul}$ for multiple rollers on a flat surface can be obtained by the following expression

$$P_{ul} \leq \frac{2}{3}(9d\sigma_u{}^2 / E) = 6d\sigma_u{}^2 / E$$

Where d = the diameter of rollers, $\sigma_u$ = the nominal ultimate tensile strength of the material, E = the modulus of elasticity of the material.

The parts of the isolation bearing used for test were made of steel with its mechanical properties: E = 30000 kips/in$^2$, $\sigma_u = 80$ kips/in$^2$, and the diameter of rollers d = 1.25 in. Thus, the design load effect per unit length is

$$P_{ul} \leq 1.6 \text{ kips/in}$$

As the length of each roller is 2.5 inches, the total length of all eight rollers is 20 inches. So the maximum allowable load of all four roller trains was determined as

$$4\times20\times1.6 = 128 \text{ kips/in} = 58 \text{ tons}$$

The design displacement capacity was 12 inches and the bearing plan dimensions were 18 inches × 18 inches only.

The buffer springs were symmetrical semi-elliptic leaf springs. The following spring parameters were selected: thickness of the leaves t= 0.36 inches, width of the leaves w= 3 inches, deflection $\delta$ = 0.7 inches, safe stress of the spring material $\sigma_s$= 80 kips/in$^2$, and the modulus of elasticity of the spring material E=30000 kips/in$^2$.

The active length of the spring was calculated by

$$l = \sqrt{\frac{4E\delta.t}{\sigma_s}}$$

The result is l=19.44 inches. Using l=20 inches, the load P of each leaf spring for a given deflection is:

$$P = \frac{8Ewt^3\delta}{3l^2}.n$$

Where n= the number of leaves. If n=2, then P= 1.96 kips.

The actual stress should meet

$$\sigma = \frac{3Pl}{2nwt^2} \leq \sigma_s$$

The result of calculation is $\sigma = 75.6 < \sigma_s = 80 kips/in^2$, which is allowable.

The stiffness of each leaf spring is given by

$$k = \frac{P}{\delta}$$

which yields $k = 2.8 kips/in$.

The experimental bearing was rotated to such that its X- and Y- axes were each at 45 degrees relative to the shaking direction, so the table's shake along a single direction could be decomposed into two direction motions. Then the working properties of the isolation bearing in two orthogonal directions could be detected.

Each pair of figures A and B shows displacement versus time and acceleration versus time, respectively, of the load block for an input earthquake wave set based on data from a given earthquake. The bases for the input wave sets are as follows: Figs. 22A, 22B - El Centro; Figs. 23A, 23B - Taft; Figs. 24A, 24B - Pacoima Dam; Figs. 25A, 25B - Northridge; Figs. 26A, 26B - Kobe; Figs. 27A, 27B - Mexico City; Figs. 28A, 28B - Chi Chi (Taiwan); and Figs. 29A, 29B - Marmara (Turkey).

Fig. 30 shows an isolation bearing 310 that is substantially similar to isolation bearing 210 of Figs. 7-12, except that the roller trains 218 and 220 are replaced by sliding shoes 318 and 320. Fig. 31 presents a detailed cross-sectional view of one possible type of sliding shoe 318, 320. Sliding shoe 318, 320 includes a bottom shoe portion 322 having a bottom surface coated by a sheet 324 of friction-reducing material, for example PTFE, and a top shoe portion 326 having a top surface coated by a sheet 328 also of friction-reducing material. The various X-axis and Y-axis wedge surface portions are preferably coated with a stainless steel sheet to maintain smooth, low-friction surfaces on which the sliding shoes can travel. The bottom shoe portion 322 includes a spherical segment recess 330 for receiving a mating portion 332 of top shoe portion 326 having a complementary spherical geometry. Such a shoe assembly allows a certain level of rotation in both X- and Y- directions defined by specific codes of bridge isolation systems. For example, the rotation angle can be 1.5 degrees or 0.03 radians. The rotation may be caused by structural deflections due to static, dynamic as well as thermal loads. An advantage of using the sliding shoes is that the vertical loads per unit area of the bearing can be largely increased. A disadvantage is that the acceleration reduction will not be as good as roller assemblies. This shoe assembly is referred to as a type A shoe design.

Fig. 32 presents a detailed cross-sectional view of another possible type of sliding shoe 318', 320'. Sliding shoe 318', 320' includes a bottom shoe portion 342 having a bottom surface coated by a sheet 344 of friction-reducing material such as PTFE, and a

top shoe portion 346 having a top surface coated by a sheet 348 also of friction-reducing material. The bottom shoe portion 342 defines a cylindrical recess 350 for receiving a rubber disc 352, and top shoe portion 346 includes a piston 354 sealed with respect to the inner wall of cylindrical recess 350 by an O-ring 356. Similar to type A shoe design, the alternative assembly also allows a certain level of rotation in both X- and Y- directions defined by specific codes of bridge isolation systems. For example, the rotation angle can be 1.5 degrees or 0.03 radians. The rotation may be caused by structural deflections due to static, dynamic as well as thermal loads. The second shoe assembly is referred to as a type B shoe design. The advantage and disadvantage of using sliding surface are the same as that of type A design. Type B design can absorb a certain amount of energy from vertical motion, whereas type A cannot. However, the type A design can allow larger rotations.

Fig. 33 shows an isolation bearing 410 of yet a further embodiment. Isolation bearing 410 is made without rollers or sliding shoes, and relies instead on the fact that the wedge surface portions of opposed cooperating wedges are designed to provide a low-friction surface-to-surface interface. For example, mating surface portions 418 and 418′ and mating surface portions 420 and 420′ can be stainless steel - PTFE interfaces.

As will be appreciated from the foregoing description, the present invention provides a seismic isolation bearing having numerous advantages. The linear slope of the various X and Y wedge surface portions gives the bearing constant acceleration and constant deceleration in its dynamic response, and the restoring force returning the intermediate and upper assemblies to their respective neutral positions is approximately constant regardless of displacement. Thus, there is a restoring force at any non-neutral position to avoid an undesirable "dead-bound" in the response. Since the natural frequency of an isolation bearing according to the present invention is largely dependent upon the slope angle of the wedge surface portions, a desirably low natural frequency can be achieved by choosing a small slope angle. Moreover, the natural frequency changes following displacement. Under the action of external excitation, the peak of absolute acceleration response is always a smaller value regardless of the input frequency and amplitude, and the amplitude of relative displacement is only slightly larger than input displacement amplitude in general conditions. If a supplemental damper is used in the

present invention, an increase in the damping ratio results in a decrease in relative displacement response but an increase in absolute acceleration response, so damping ratio must be chosen to achieve a desired response. Finally, the isolation bearing of the present invention saves space over prior art isolation bearings while providing a high load capacity and a self-restoring action under gravity.

What is claimed is:

1. An isolation bearing comprising:

a lower assembly;

an intermediate assembly mounted on said lower assembly for travel in opposite X-axis directions relative to an X-axis neutral position;

X-axis wedge means acting between said lower and intermediate assemblies to bias said intermediate assembly toward said X-axis neutral position by gravitational loading when said intermediate assembly travels away from said X-axis neutral position;

an upper assembly mounted on said intermediate assembly for travel in opposite Y-axis directions relative to a Y-axis neutral position; and

Y-axis wedge means acting between said intermediate and upper assemblies to bias said upper assembly toward said Y-axis neutral position by gravitational loading when said upper assembly travels away from said Y-axis neutral position.

2. The isolation bearing according to claim 1, further comprising an energy dissipation device connected between said lower assembly and said intermediate assembly.

3. The bearing system according to claim 2, wherein said energy dissipation device is an elastomeric damper, a fluid damper, a friction damper, or a metallic damper.

4. The bearing system according to claim 1, further comprising an energy dissipation device connected between said intermediate assembly and said upper assembly.

5. The bearing system according to claim 4, wherein said energy dissipation device is an elastomeric damper, a fluid damper, a friction damper, or a metallic damper.

6. The isolation bearing according to claim 1, wherein said X-axis wedge means includes a pair of X-axis wedge surface portions fixed relative to said lower assembly, said pair of X-axis wedge surface portions sloping downwardly in approaching X-axis directions.

7. The isolation bearing according to claim 1, wherein said X-axis wedge means includes a pair of X-axis wedge surface portions fixed relative to said intermediate assembly, said pair of X-axis wedge surface portions sloping upwardly in approaching X-axis directions.

8. The isolation bearing according to claim 6, wherein said X-axis wedge means includes another pair of X-axis wedge surface portions fixed relative to said intermediate assembly, said other pair of X-axis wedge surface portions sloping upwardly in approaching X-axis directions.

9. The isolation bearing according to claim 8, wherein each of said pair of X-axis wedge surface portions and each of said other pair of X-axis wedge surface portions is linearly sloped.

10. The isolation bearing according to claim 1, wherein said Y-axis wedge means includes a pair of Y-axis wedge surface portions fixed relative to said intermediate assembly, said pair of Y-axis wedge surface portions sloping downwardly in opposite Y-axis directions toward one another.

11. The isolation bearing according to claim 1, wherein said Y-axis wedge means includes a pair of Y-axis wedge surface portions fixed relative to said upper assembly, said pair of Y-axis wedge surface portions sloping upwardly in opposite Y-axis directions toward one another.

12. The isolation bearing according to claim 10, wherein said Y-axis wedge means includes another pair of Y-axis wedge surface portions fixed relative to said upper assembly, said other pair of Y-axis wedge surface portions sloping upwardly in opposite Y-axis directions toward one another.

13. The isolation bearing according to claim 12, wherein each of said pair of Y-axis wedge surface portions and each of said other pair of Y-axis wedge surface portions is linearly sloped.

14. The bearing system according to claim 1, wherein said intermediate assembly is mounted on said lower assembly by at least one cylindrical roller having a horizontal axis of rotation, and said upper assembly is mounted on said intermediate assembly by at least one cylindrical roller having a horizontal axis of rotation.

15. The isolation bearing according to claim 14, wherein said at least one cylindrical roller for mounting said intermediate assembly on said lower assembly contacts said X-axis wedge means, and said at least one cylindrical roller for mounting said upper assembly on said intermediate assembly contacts said Y-axis wedge means.

16. The isolation bearing according to claim 8, wherein each of said pair of X-axis wedge surface portions associated with said lower assembly is connected to a respective one of said other pair of X-axis wedge surface portions associated with said intermediate assembly by at least one cylindrical roller having a horizontal axis of rotation.

17. The isolation bearing according to claim 16, wherein said at least one cylindrical roller includes a roller train having a plurality of joined cylindrical rollers.

18. The isolation bearing according to claim 12, wherein each of said pair of Y-axis wedge surface portions associated with said intermediate assembly is connected to a respective one of said other pair of Y-axis wedge surface portions associated with said upper assembly by at least one cylindrical roller having a horizontal axis of rotation.

19. The isolation bearing according to claim 18, wherein said at least one cylindrical roller includes a roller train having a plurality of joined cylindrical rollers.

20. The bearing system according to claim 1, wherein said intermediate assembly is mounted on said lower assembly by at least one sliding shoe, and said upper assembly is mounted on said intermediate assembly by at least one sliding shoe.

21. The isolation bearing according to claim 20, wherein said at least one sliding shoe for mounting said intermediate assembly on said lower assembly contacts said X-axis wedge means, and said at least one sliding shoe for mounting said upper assembly on said intermediate assembly contacts said Y-axis wedge means.

22. The isolation bearing according to claim 8, wherein each of said pair of X-axis wedge surface portions associated with said lower assembly is connected to a respective one of said other pair of X-axis wedge surface portions associated with said intermediate assembly by a sliding shoe.

23. The isolation bearing according to claim 22, wherein said sliding shoe includes a bottom surface of friction reducing material contacting said X-axis wedge surface portions associated with said lower assembly and a top surface of friction reducing material contacting said X-axis wedge surface portions associated with said intermediate assembly.

24. The isolation bearing according to claim 12, wherein each of said pair of Y-axis wedge surface portions associated with said intermediate assembly is connected to a respective one of said other pair of Y-axis wedge surface portions associated with said upper assembly by a sliding shoe.

25. The isolation bearing according to claim 24, wherein said sliding shoe includes a bottom surface of friction reducing material contacting said Y-axis wedge surface portions associated with said intermediate assembly and a top surface of friction reducing material contacting said Y-axis wedge surface portions associated with said upper assembly.

26. The isolation bearing according to claim 9, wherein each of said pair of X-axis wedge surface portions and a cooperating one of said other pair of X-axis wedge surface portions are slidably connected by a low-friction interface therebetween.

27. The isolation bearing according to claim 13, wherein each of said pair of Y-axis wedge surface portions and a cooperating one of said other pair of Y-axis wedge surface portions are slidably connected by a low-friction interface therebetween.

28. The isolation bearing according to claim 14, further comprising a first self-cleaning mechanism connected to said at least one cylindrical roller on which said intermediate assembly is mounted for clearing dirt and debris from said X-axis wedge means, and a second self-cleaning mechanism connected to said at least one cylindrical roller on which said upper assembly is mounted for clearing dirt and debris from said Y-axis wedge means.

29. The isolation bearing according to claim 1, further comprising a water drainage system for draining water away from said X-axis wedge means and said Y-axis wedge means.

30. The isolation bearing according to claim 1, further comprising a housing system including a plurality of protective caps and sealing strips around the perimeter of said bearing.

31. The isolation bearing according to claim 30, wherein said plurality of protective caps and sealing strips includes replaceable protective caps and sealing strips designed to be torn off during an earthquake.

32. The isolation bearing according to claim 30, wherein said plurality of protective caps and sealing strips includes replaceable protective caps and sealing strips mounted on spring-hinges biased toward a normally closed position but designed to open during an earthquake.

33. The isolation bearing according to claim 14, further comprising a pair of stop blocks fixed to said lower assembly and spaced apart in the X-axis direction for limiting rolling travel of said at least one cylindrical roller upon which said intermediate assembly is mounted, whereby relative X-axis motion between said intermediate and lower assemblies must change from rolling motion to sliding motion in a given X-axis direction upon abutment of said at least one roller with one of said pair of stop blocks.

34. The isolation bearing according to claim 14, further comprising a pair of stop blocks fixed to said intermediate assembly and spaced apart in the Y-axis direction for limiting rolling travel of said at least one cylindrical roller upon which said upper assembly is mounted, whereby relative Y-axis motion between said upper and intermediate assemblies must change from rolling motion to sliding motion in a given Y-axis direction upon abutment of said at least one roller with one of said pair of stop blocks.

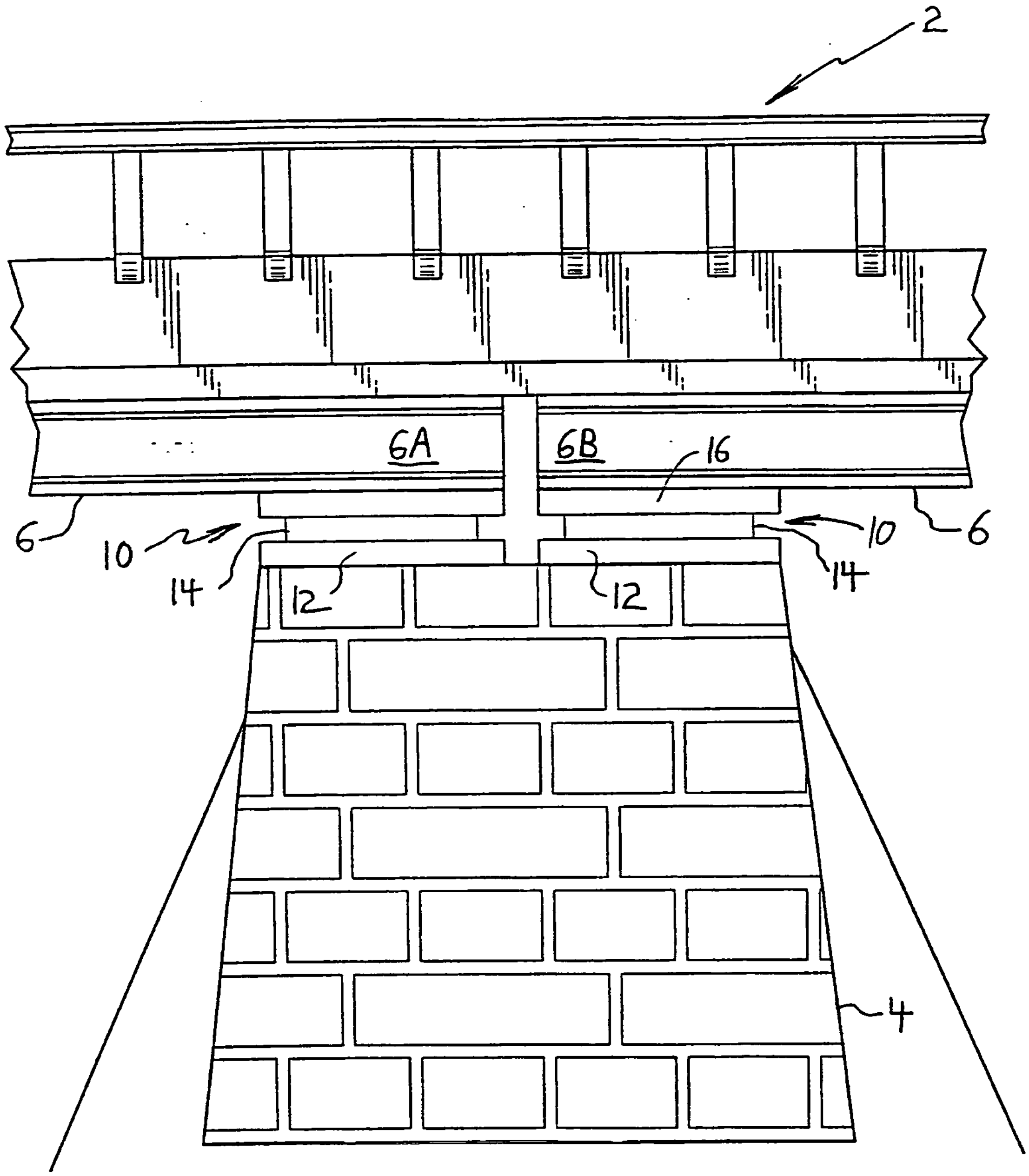
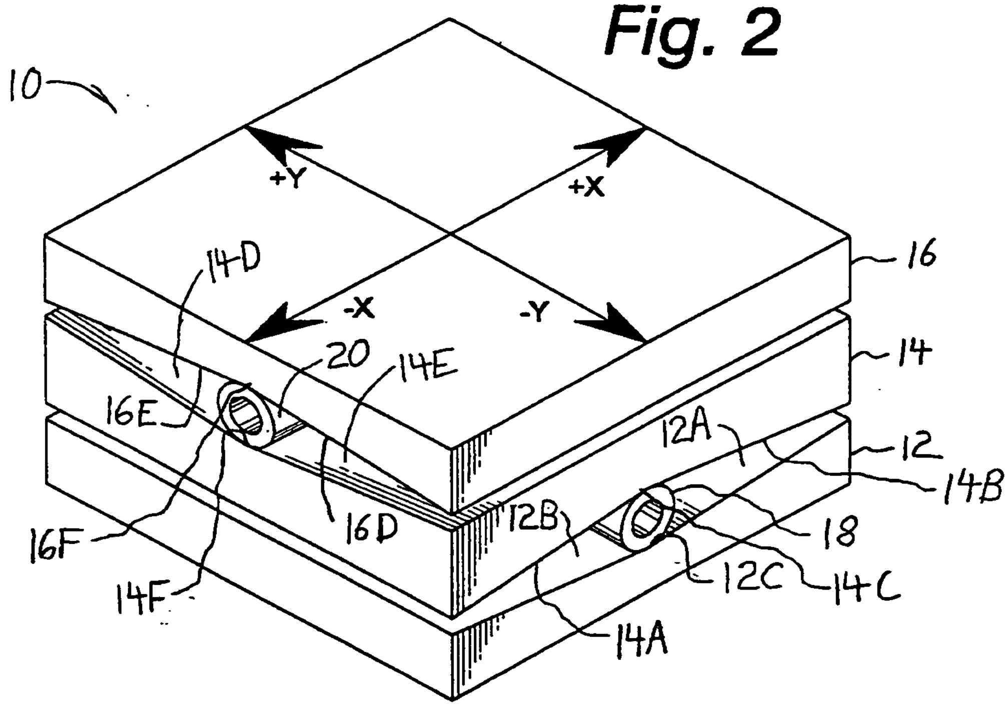



Fig. 1

Fig. 2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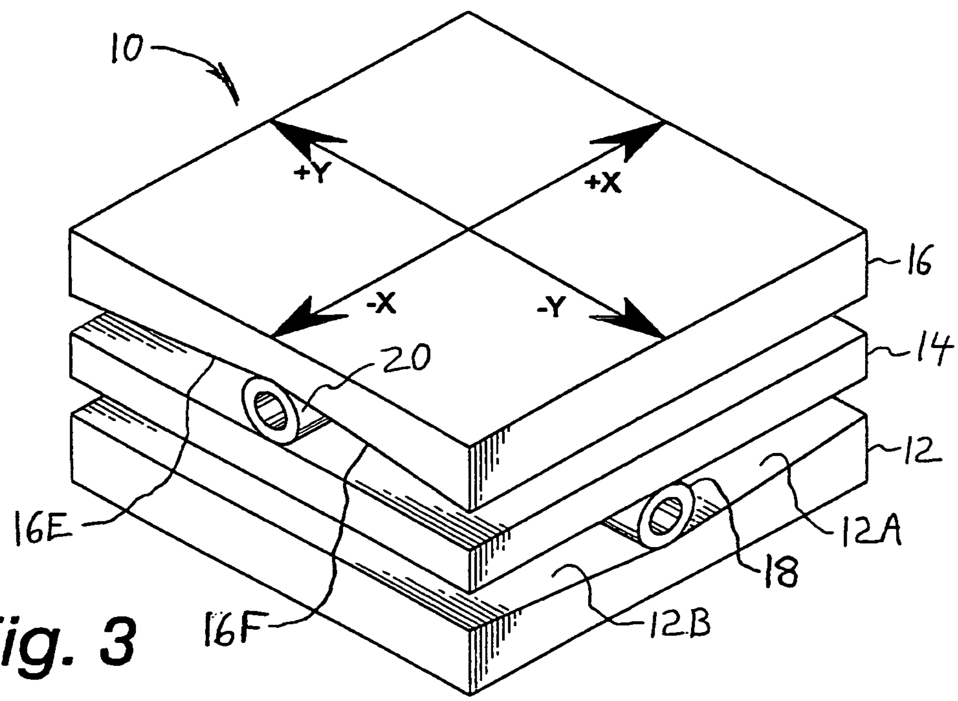
+Y
+X
-X
-Y
16
14
12
14D
20
14E
16E
12A
14B
12B
18
16F
16D
12C
14C
14F
14A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+X
-X
-Y
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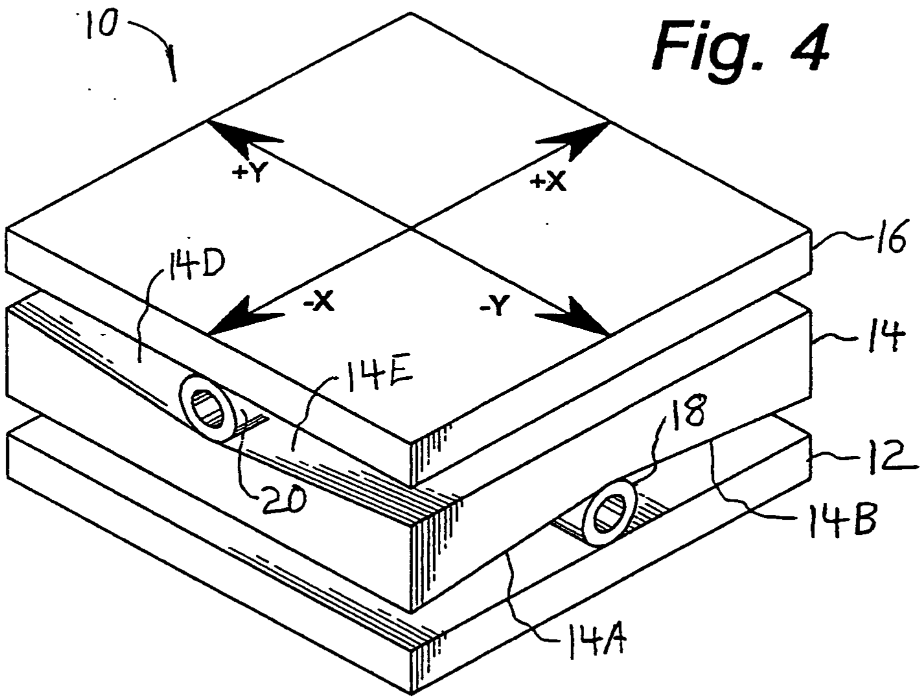
14
12
20
16E
12A
18
16F
12B

Fig. 3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+X
-X
-Y
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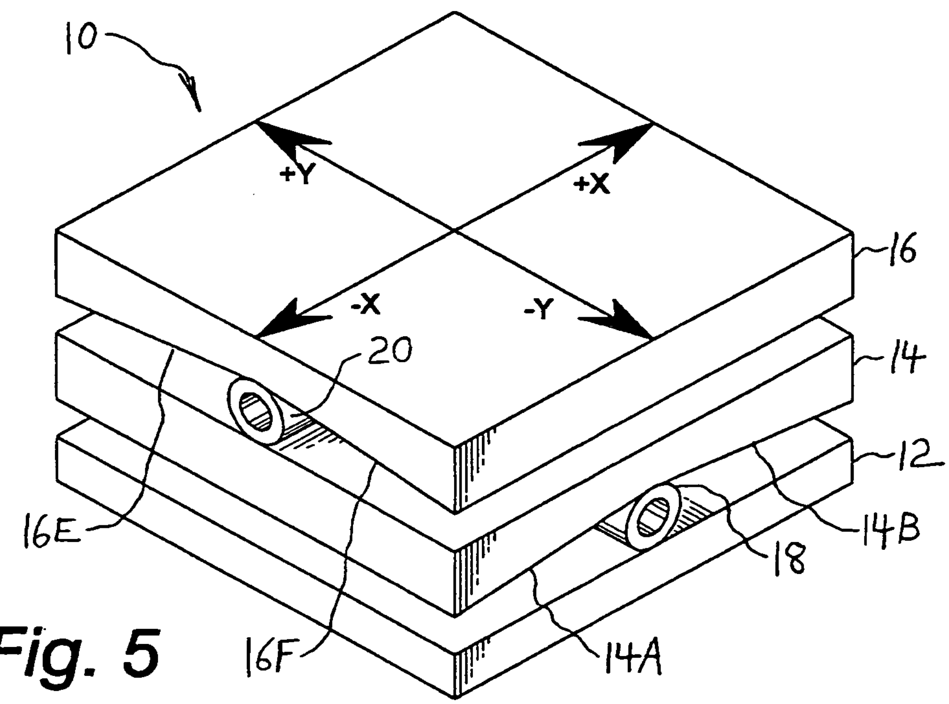
14D
14
14E
18
12
20
14B
14A

Fig. 4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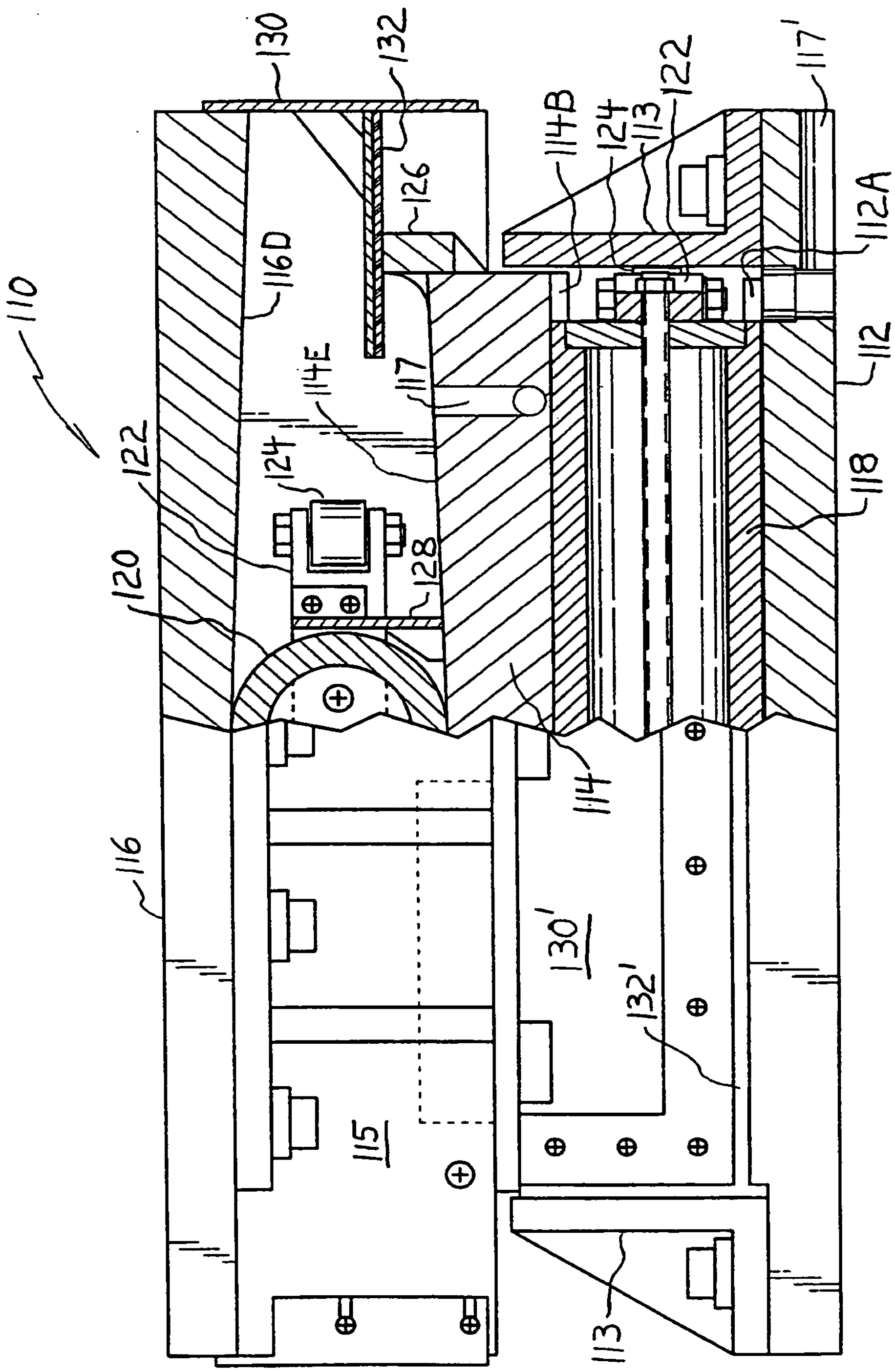
+X
-X
-Y
16
20
14
12
16E
14B
18
16F
14A

Fig. 5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114B
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122
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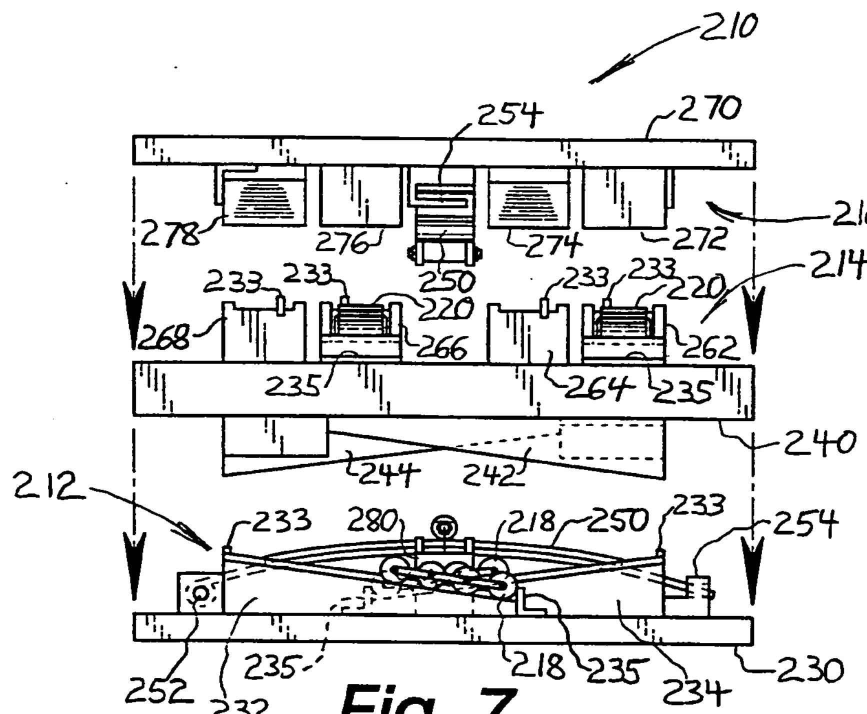
112A
112
118
114
116
115
130'
132'
113

Fig. 6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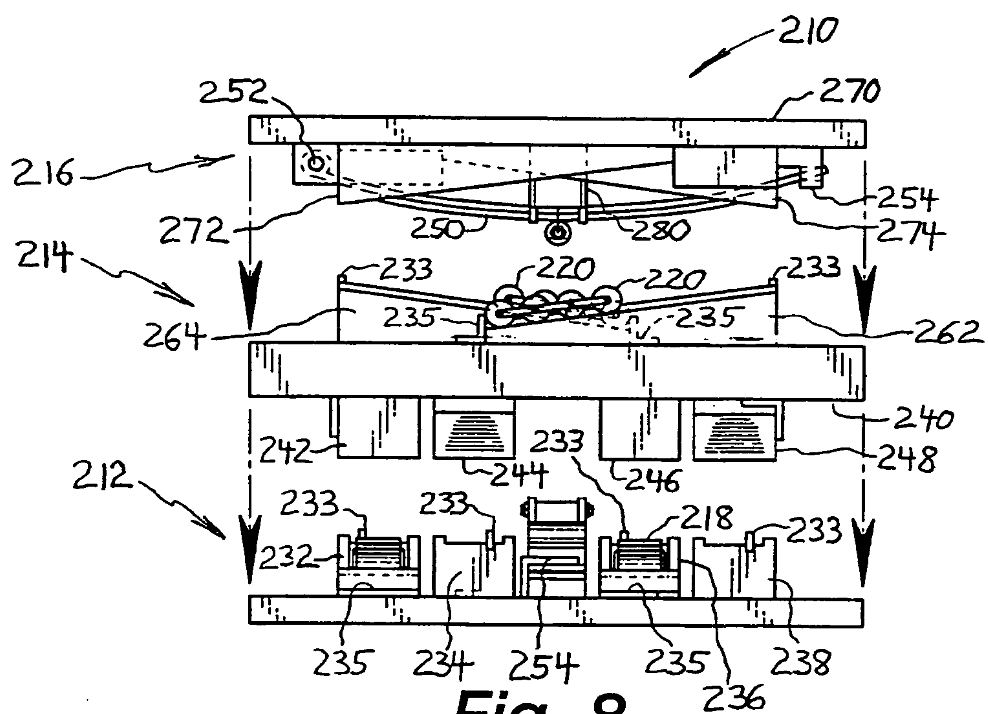
230
232

Fig. 7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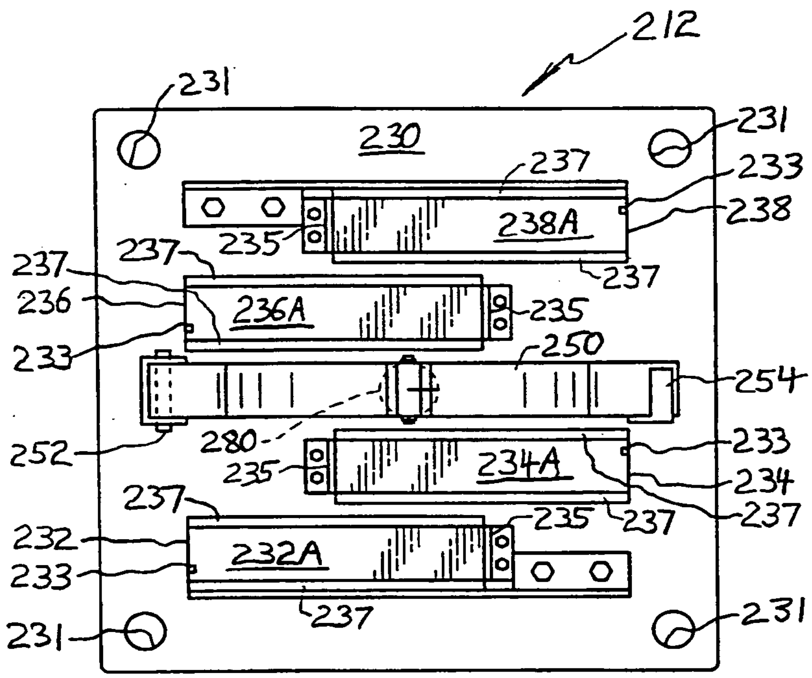
238

Fig. 8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232A
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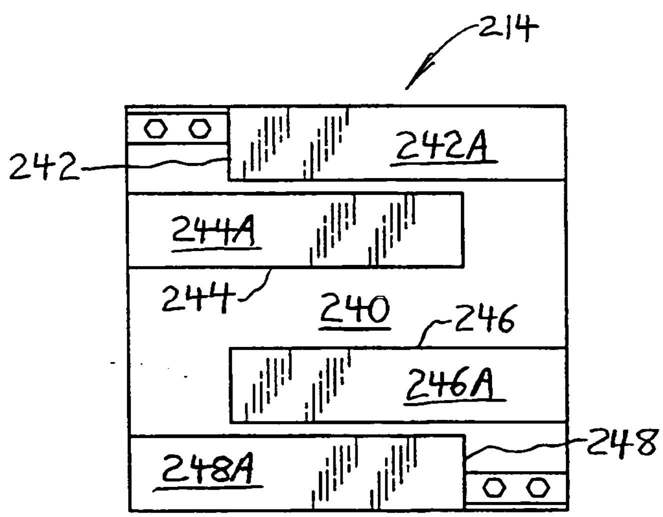
Fig. 9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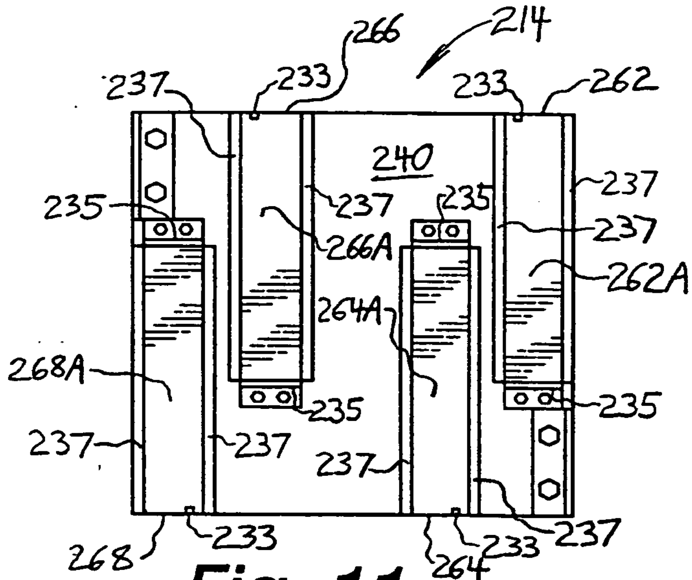
248A

Fig. 10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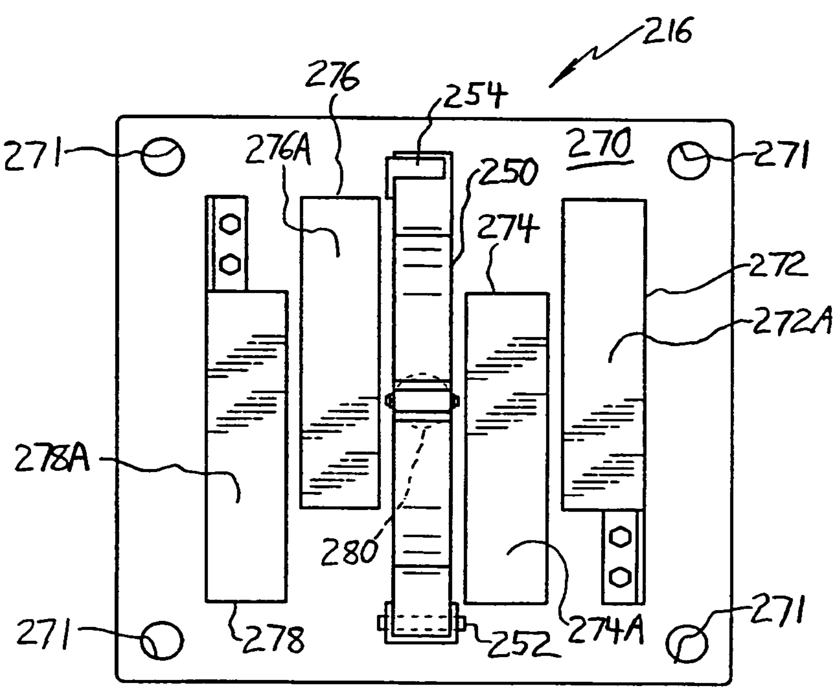
264
233
237

Fig. 11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274A
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Fig. 12

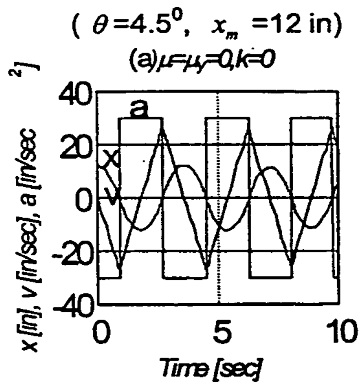



Fig. 13A

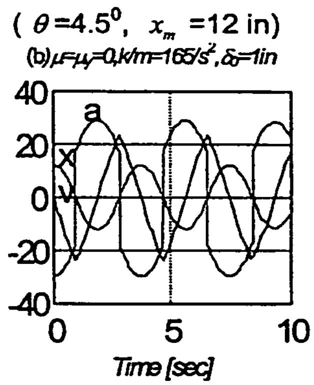



Fig. 13B

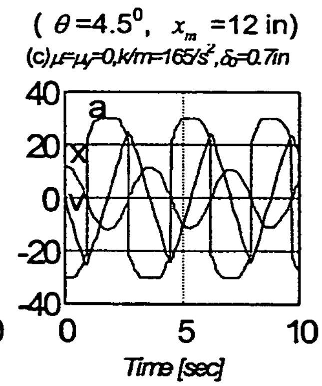



Fig. 13C

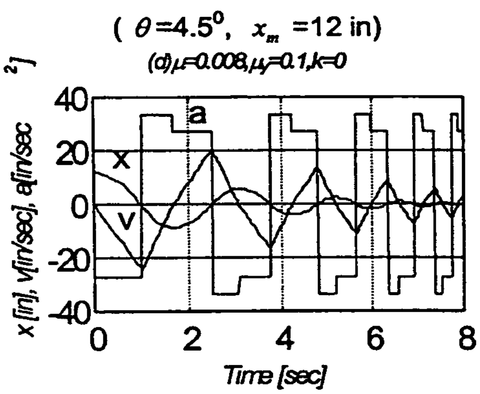



Fig. 13D

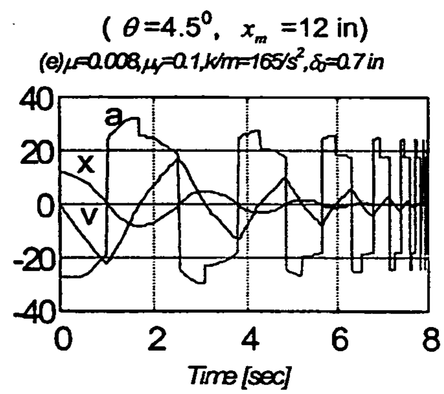



Fig. 13E

Fig. 14A

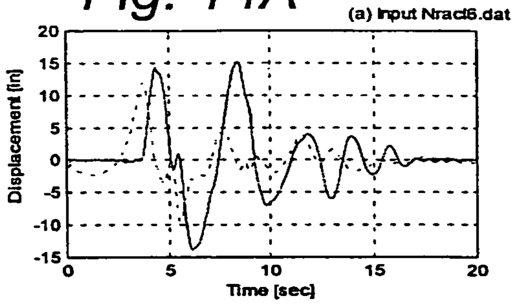



Fig. 14B

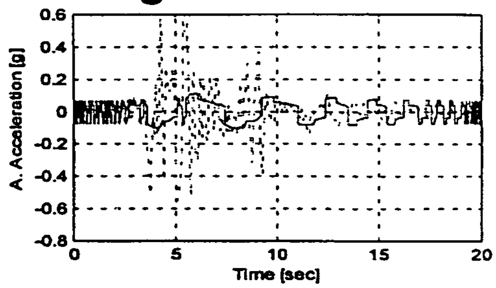



Fig. 15A

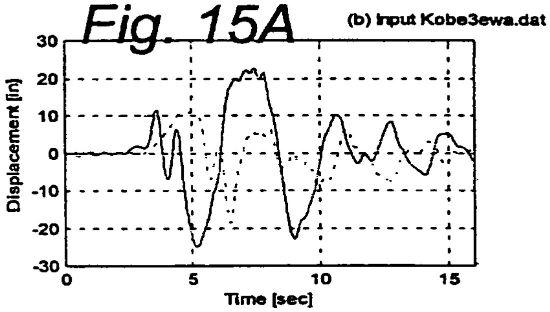



Fig. 15B

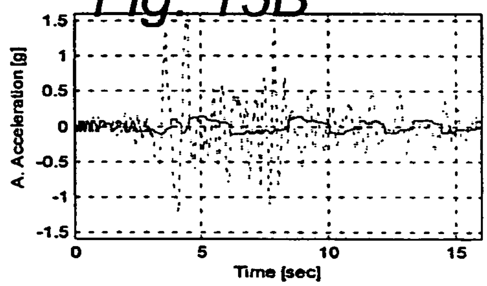



Fig. 16A

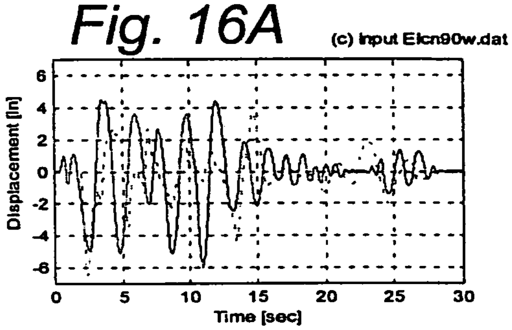



Fig. 16B

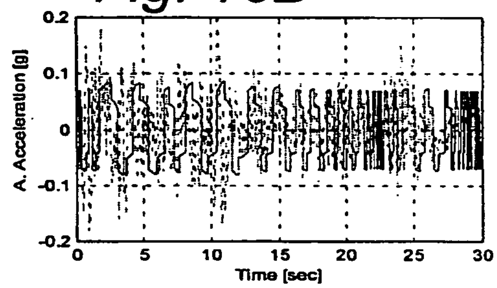



Fig. 17A

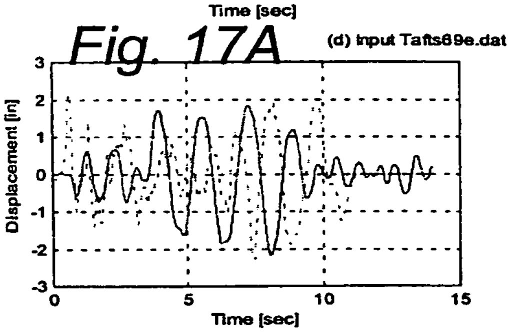
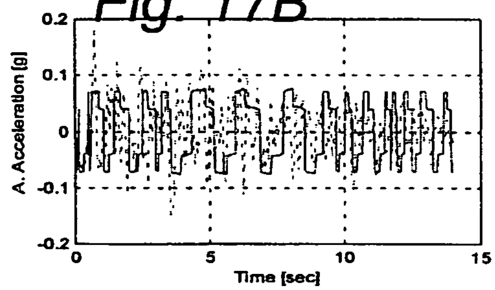



Fig. 17B




Input
Response

Fig. 18A (a) c=0 kips.sec/in

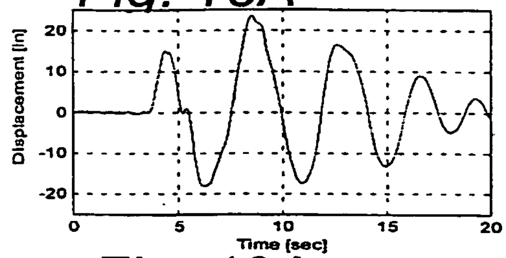



Fig. 18B

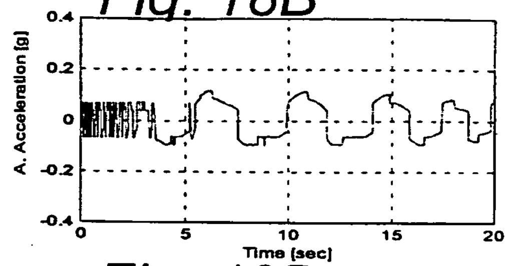



Fig. 19A (b) c=0.012 kips.sec/in

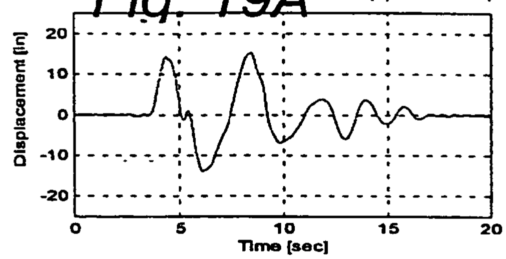



Fig. 19B

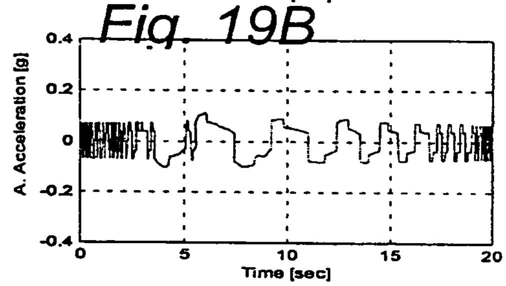



Fig. 20A (c) c=0.12 kips.sec/in

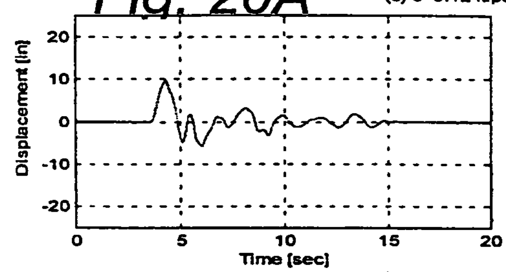



Fig. 20B

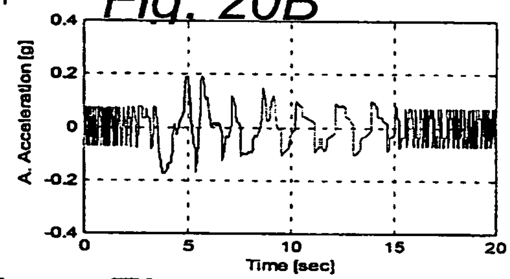



Fig. 21A (d) c=0.24 kips.sec/in

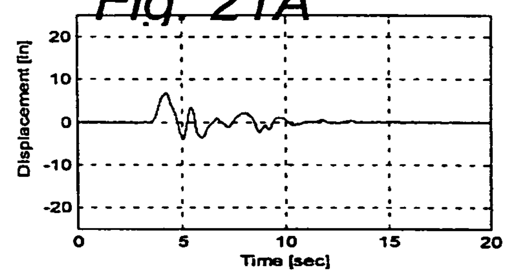
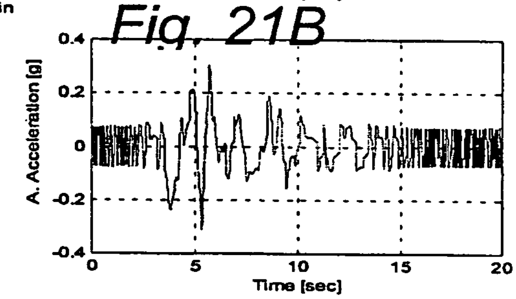



Fig. 21B




( Input Nracl6.dat)

(a) Input EL Centro

Fig. 22A

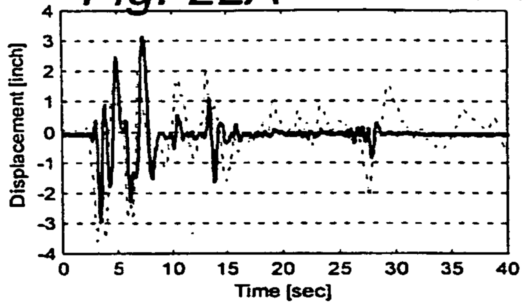
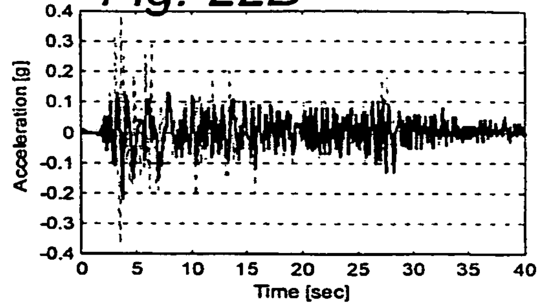



Fig. 22B




(b) Input Taft

Fig. 23A

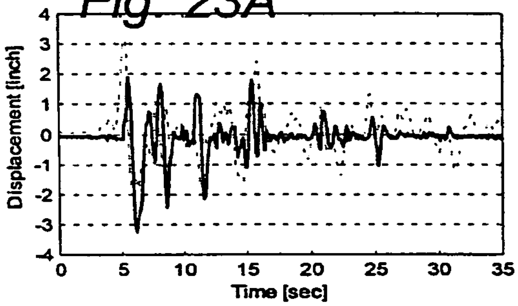
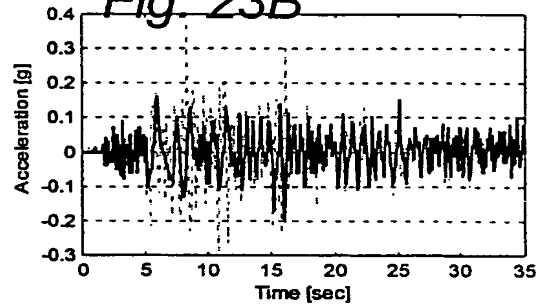



Fig. 23B




(c) Input Pacoima Dam

Fig. 24A

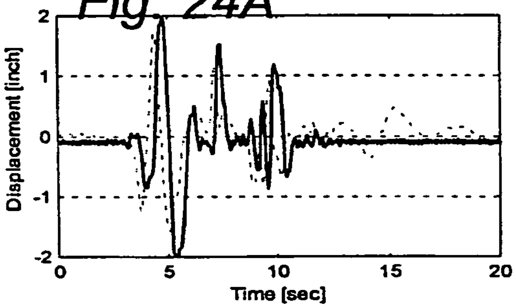
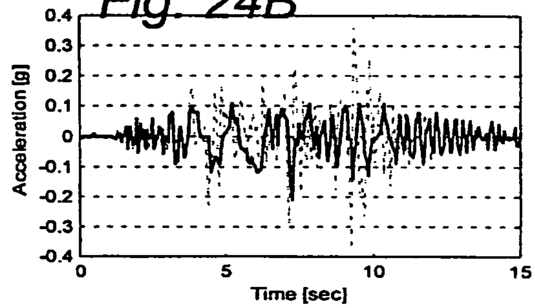



Fig. 24B




(d) input Nothridge

Fig. 25A

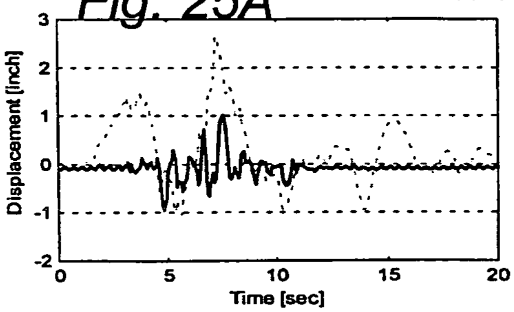
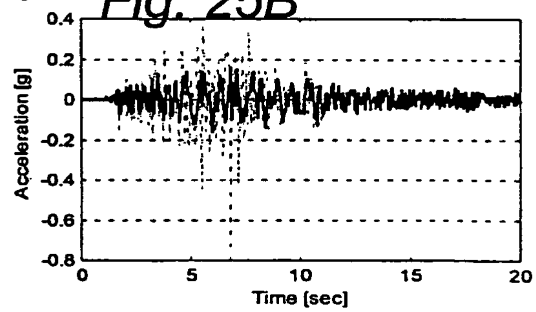



Fig. 25B




Input Response

Fig. 26A

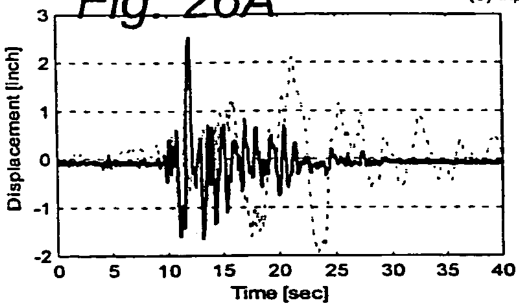



Fig. 26B

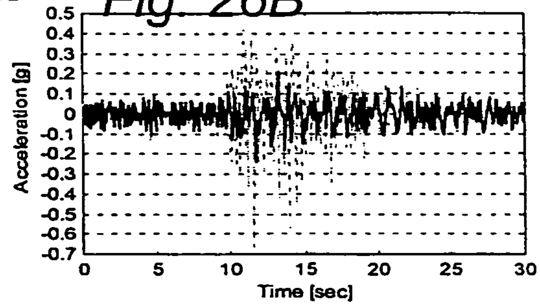



Fig. 27A

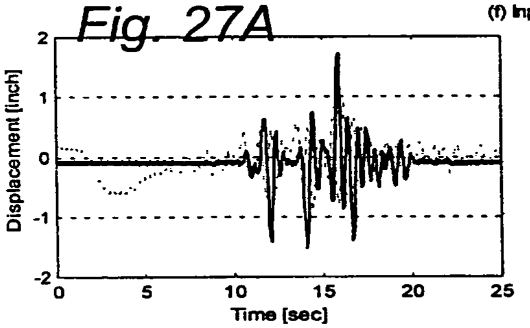



Fig. 27B

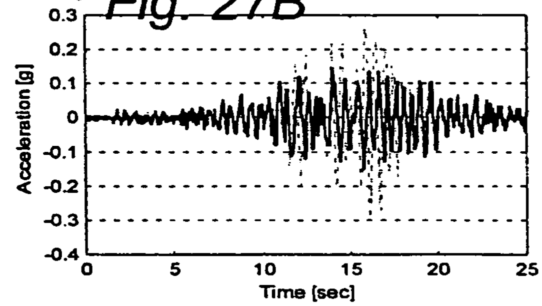



Fig. 28A

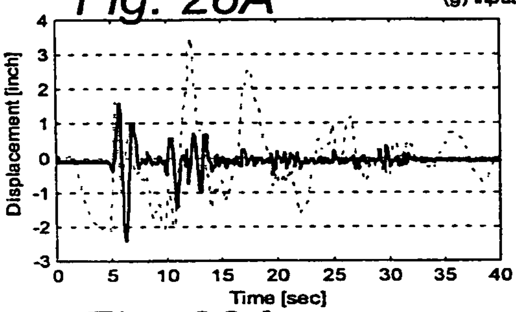



Fig. 28B

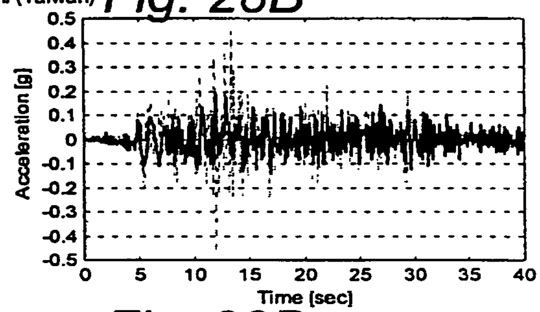



Fig. 29A

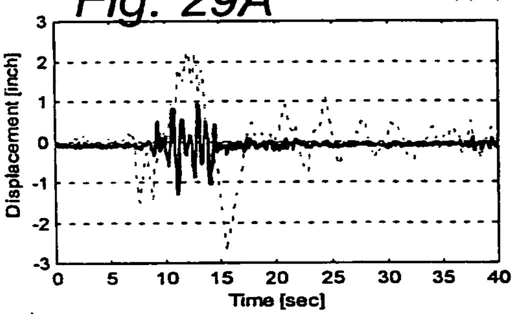
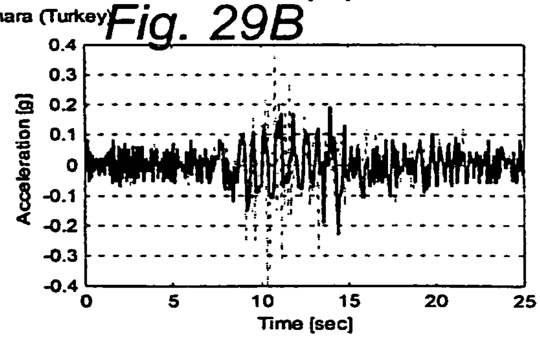



Fig. 29B




Input Response

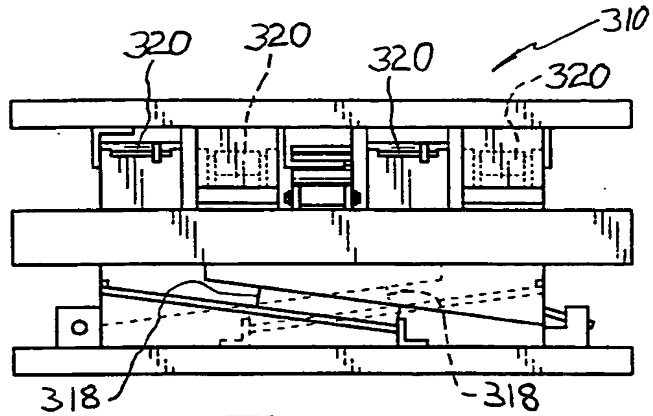



Fig. 30

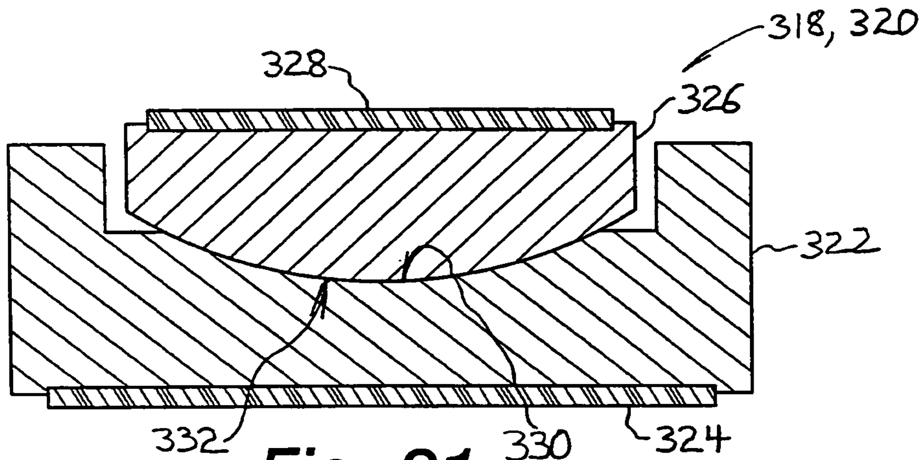



Fig. 31

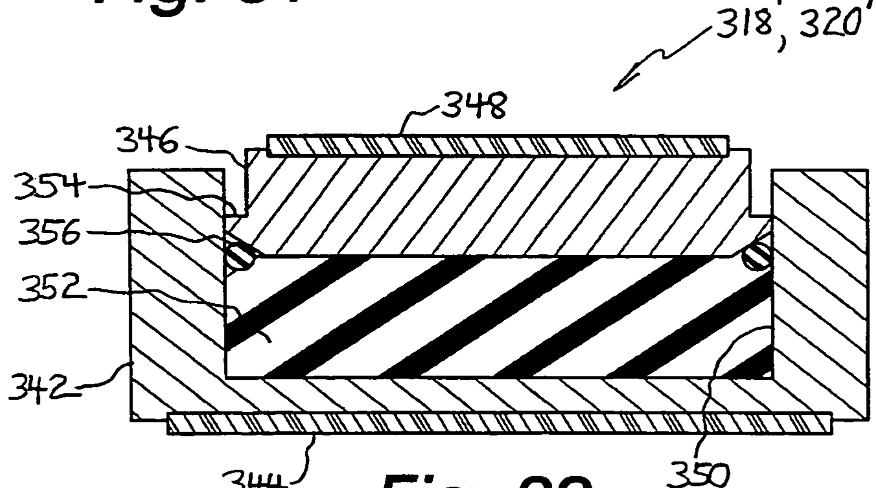



Fig. 32

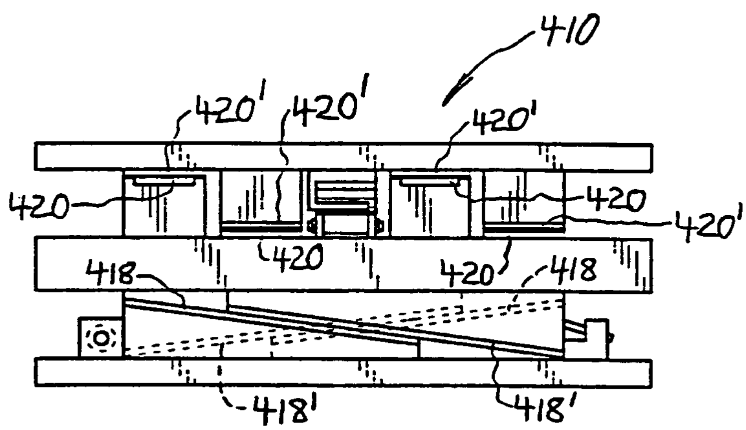



Fig. 33